Perspectives from the NA62 experiment

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Introduction

NA62 experiment approved to run until LS2
  • **main goal**: measuring the BR(K$^+ \to \pi^+ \nu \bar{\nu}$) with 10% accuracy;
  • a broad physics program: searches for LFV/LNV modes, hidden sector particles

Present talk covers possible plans for dedicated searches in **Run3**

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![Diagram showing accelerator schedule and run periods]

**Current Run**
- LHC: Run 2, LS2
- SPS

**Run3**
- LHC: Run 3, LS3 (This talk)
- SPS stop

**Run4**
- LHC
- SPS stop

NA62: K$^+ \to \pi^+ \nu \bar{\nu}$, LNV/LFV decays, hidden sector searches in kaon decays
NA62 experiment: the goal

$K \to \pi \nu \bar{\nu}$ decays: FCNC $s\to d$ loops, theoretically clean, sensitive to various NP models


\[
\begin{align*}
\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) &= (8.39 \pm 0.30) \cdot 10^{-11} \left( \frac{|V_{cb}|}{0.0407} \right)^{2.8} \left( \frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11} \\
\text{BR}(K_L \to \pi^0 \nu \bar{\nu}) &= (3.36 \pm 0.05) \cdot 10^{-11} \left( \frac{|V_{ub}|}{0.00388} \right)^2 \left( \frac{|V_{cb}|}{0.0407} \right)^2 \left( \frac{\sin \gamma}{\sin 73.2^\circ} \right)^2 = (3.4 \pm 0.6) \cdot 10^{-11}
\end{align*}
\]

Experimental status:

\[
\begin{align*}
\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) &= (17.3^{+11.5}_{-10.5}) \times 10^{-11} \quad \text{Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)} \\
\text{BR}(K_L \to \pi^0 \nu \bar{\nu}) &< 2.6 \times 10^{-8} \quad \text{90\% C.L.} \quad \text{Phys. Rev. D 81, 072004 (2010)}
\end{align*}
\]

NA62 goal: measure $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})$ with $\mathcal{O}(10\%)$ total uncertainty
NA62: a high-intensity setup

Collect 100 $\pi\nu\bar{\nu}$ events in 2 years of data taking, 10% signal acceptance ($10^{13}$ $K^+$)

High-intensity proton-produced charged hadron beam:

$10^{12}$ 400-GeV $p/s$ from $\sim$3.5-s SPS spills onto a Be target

Secondary 75-GeV beam selected: 1% momentum bite, $X,Y$ divergence $< 100$ $\mu$rad

Can track 750 MHz beam ($6%$ $K^+$) and sustain $\sim$5 MHz $K^+$ decay in a 60-m long volume in vacuum

Excellent time resolution to match beam and daughter particle information

Kinematics, rejection of main $K$ modes $10^4$—$10^5$ via kinematic reconstruction

PID capability, $\mu$ vs $\pi$ rejection of $O(10^7)$ for $15 < p(\pi^+) < 35$ GeV

High-efficiency veto, $10^8$ rejection of $\pi^0$’s for $E(\pi^0) > 40$ GeV
NA62: a high-intensity setup
Status/timescale for $K \to \pi \nu \nu$

Run in 2015:
- Commissioning of L0 trigger
- Run up to nominal intensity, $3.3 \times 10^{12}$ POT/spill, 3.5-s effective-length spill

Running in 2016:
- Stable running at 20% of the nominal beam intensity

Data already collected: sensitivity to BR($K \to \pi \nu \nu$) up to $10^{-9}$

End of 2016: reach SM-expectation sensitivity, $O(10^{-10})$

End of 2017 run: improve (by much) on present state of the art (BNL measurement)

End of 2018 run: measurement of BR at 10%
Physics from NA62 up to 2018, besides $K \rightarrow \pi \nu \nu$

Such high-intensity, high-performance setup might be suited for other NP searches

LFV/LNV studies with $10^{13} K^+ \rightarrow SES \ 10^{-12}$, improve by $\sim x100$ on past results

ultra-rare/forbidden $\pi^0$ decays, $10^{11}$ tagged $\pi^0$’s $\rightarrow SES \ 10^{-10}$, improve by $\sim x100$

chiral perturbation theory studies from other kaon decays

Trigger bandwidth for final states other than “$\pi^+ + E_{\text{miss}}$” anyway limited

15 MHz single-tracks: ask 1 track, no muon, $E_{\text{miss}}$ and reduce L0 to $\sim 750$ KHz

Including calibration and control triggers, little free bandwidth (max 1 MHz)

Some LFV/LNV studies can be performed because involve low-bandwidth triggers...

3 daughter tracks at SES $\sim 10^{-11}$: $K^+ \rightarrow \pi^\pm \mu^\mp e^\mp$, $K^+ \rightarrow \pi^0 e^+ e^-$, $K^+ \rightarrow \pi^\pm \mu^\mp \mu^\mp$

... others because can be made in parasitic mode with the main trigger:

search for heavy neutral leptons in $K^+ \rightarrow \mu^+ \nu_h$, $K^+ \rightarrow e^+ \nu_h$

search for $\pi^0 \rightarrow \nu_1 \nu_2$, NA62 sensitive to BR($\pi^0 \rightarrow$ invisible) at $10^{-8}$ or better
An example from a dedicated trigger: $K \rightarrow \pi^+ \mu^+ \mu^-$

Sample from 2016 data: $\sim$60k bursts ($\sim$2 week-equivalent) at $\sim$18% intensity

Improvements on NA48/2: mass resolution better by $\sim$ a factor of 2
BR is $O(10^{-7})$, expects improved sensitivity on hidden sector search, $K \rightarrow \pi^+ \chi, \chi \rightarrow \mu^+\mu^-$

Basis for the search for LNV decay $K \rightarrow \pi^- \mu^+\mu^-$.

NA62 preliminary

700 $K_{\pi\mu\mu}$ events
$\sigma_M = 1.3$ MeV/$c^2$

Events/0.5 MeV/$c^2$

Data

MC $K_{3\pi}$

MC $K_{\pi\mu\mu}$

MC $K_{\mu4}$

NA48/2 2003–2004 data (preliminary; paper in preparation)

3.5k $K_{\pi\mu\mu}$ events; $\sigma_M = 2.5$ MeV

Events/0.5 MeV/$c^2$
Physics at NA62 in Run 3

A rich field to be explored with minimal/no upgrades to the present setup

1. Present setup for $K^+$ beam + dedicated triggers: complete LFV/LNV high-sensitivity studies based on $K^+/\pi^0$:

\[
\begin{align*}
K^+ &\rightarrow \pi^+\mu^+\bar{e},
K^+ &\rightarrow \pi^-\bar{\mu}^+e^+,
K^+ &\rightarrow \pi^-e^+e^+,
K^+ &\rightarrow \pi^-\mu^+\mu^+ (+\text{ radiative modes}) \\
\pi^0 &\rightarrow \mu e, \ 3\gamma, \ 4\gamma, \ ee, \ eeee
\end{align*}
\]

2. Year-long run in “beam-dump” mode, new program of NP searches for MeV-GeV mass hidden-sector candidates: Dark photons, Heavy neutral leptons, Axions/ALP’s, etc.
Hidden sector at NA62: motivations

If DM is a thermal relic from hot early universe, can hunt for it in particle-physics: search for non-gravitational interactions DM-SM

A mediator of a hidden sector might exist, inducing DM-SM field (feeble) interactions
many possible dynamics: vector ($A'$, aka dark photon), neutrino (HNL), axial (ALP $a$), scalar..

Various experimental hints for hidden sector at MeV-GeV, e.g., $a_\mu$ 3.5-$\sigma$ discrepancy:

- Might be due to a dark photon $A'$ ...
- ...or to an ALP $a$ enhancing light-by-light?

Model dependence: experimentally driven approach

Feeble interaction: ultra-suppressed production rate, very long-lived states
E.g.: 1-GeV mass HNL, $\tau \sim 10^{-5}$--$10^{-2}$ s, decay length $\sim 10$--10000 Km at SPS energies, suppression at production $10^{-7}$--$10^{-10}$
NA62 perfectly suited for hidden sector searches

High-intensity 400-GeV proton beam → boost charm/beauty, other meson production

$10^{18}$ POT / nominal year: $10^{12}$ POT/sec on spill, 3.5-s/16.8 s, 100 days/year, 60% run efficiency

$10^{15}$ $D\,(s), 10^{14}$ $K, 10^{18}$ $\pi^0/\eta/\eta'/\Phi/\rho/\omega$ with ratios $6.4/0.68/0.07/0.03/0.94/0.95$ (& B mesons, too)

Compact beam dump: ~11 $\lambda_i$ Cu-based beam-defining collimator (TAX)

Radioprotection-compliant even if target removed

Decay volume ~ 60 m long (in vacuum):
Reasonable acceptance to long-lived states

High-resolution tracking, PID, vetoing: high sensitivity to closed signatures
Search for visible decays of long-lived $A'$

Assume $2 \times 10^{18}$ 400-GeV POT:

- search for displaced, dilepton decays of dark photons, $A' \rightarrow \mu\mu$
- include trigger/acceptance/selection efficiency
- assume zero-background, evaluate expected 90%-CL exclusion plot

| $A'$ coupling to ordinary $\gamma|^{2}$

---

Sensitivity expected to be even higher:
1. including direct QCD production of $A'$
2. Including $A'$ production in the dump (only target considered here)

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$A'$ mass (MeV/c²)
Search for visible decays of heavy neutral leptons

Assume $2 \times 10^{18}$ 400-GeV POT:

- search for displaced, leptonic decays $\text{HNL} \rightarrow \pi e, \pi \mu$
- include trigger/acceptance/selection efficiency
- assume zero-background, evaluate expected 90%-CL exclusion plot

$|\text{HNL coupling to } \mu|^2$

Sensitivity expected to be even higher after including search for other decay channels (semileptonic, hadronic modes)
Search for visible decays of ALP’s

Assume $1.3 \times 10^{16}$ $(3.9 \times 10^{17})$ POT corresponding to 1 day (1 month) runs:
Study ALP Primakoff production [JHEP 1602 (2016) 018] at target
search for ALP-decay to $\gamma \gamma$ in NA62 fiducial volume, account for geometrical acceptance
assume zero-background, evaluate expected 90%-CL exclusion plot
On the zero-background assumption

Present sensitivity projections in the zero-background assumption

Study one of the most relevant sources of background using data:
muons from the beam “halo” (very upstream $\pi$, K decays)
for the present $K^+$ beam, expects $\sim$3 MHz $\mu^+$ and $\sim$150 KHz $\mu^-$ in the LKr acceptance

Test background rejection capability with present data searching for $A' \rightarrow \mu\mu$
background from combinatorial pairing of halo muons

Trigger parasitic to $\pi\nu\nu$:
require 2 muons downstream (in time within 10 ns) & LKr Energy < 20 GeV
trigger efficiency included in sensitivity projections previously shown
Search for $A' \rightarrow \mu\mu$: test on 2016 data

Statistics corresponds to $\sim 10^{15}$ POT’s

Track quality + acceptance cuts: forward detectors, CHOD, LKr, MUV3 associated to CHOD, LKr hits in time

Vertex quality: two-track distance < 1 cm

Vertex position: $105 < Z < 165$ m

Test if total momentum stems from target

Background from $K, \pi$ decays concentrated around beam after final collimator
Search for \( A' \rightarrow \mu\mu \): test on 2016 data

Statistics corresponds to \(~10^{15}\) POT’s

**Track quality + acceptance cuts:** forward detectors, CHOD, LKr, MUV3 associated to CHOD, LKr hits in time

**Vertex quality:** two-track distance < 1 cm

**Vertex position:** \( 105 < Z < 165 \text{ m} \)

Test if total momentum stems from target

Further event-level veto conditions:
- Additional energy in the LKr < 2 GeV
- Veto on forward / large angle calorimeters
- Veto on charged anti counter

No events selected in the signal region (even with standard \( K^+ \) beam)
MeV-GeV ALP at NA62: test with 2015 data

Data from a few-hour run with closed tax at full intensity: $\sim 10^{14}$ POT’s

Use correlation of ALP energy and $\theta$ angle for background rejection

Result: can achieve the zero-background limit
Conclusions: physics at NA62 after LS2

Assuming fulfillment of main goal, BR(K-→πνν), a broad physics program at NA62 after LS2

1. Present K⁺ beam and dedicated triggers for one-year-long data taking:
   - LFV and LNV to SES ~ 10⁻¹² from K and π⁰ decays
   - Ultra-rare/forbidden π⁰ decays

2. Year-long data-taking (10¹⁸ POT) in beam dump mode provides sensitivity to NP models:
   - Dark photons, Heavy Neutral Leptons, Axion-like particles, etc.

Expected sensitivity superior to that from other initiatives in the same time range

Data demonstrate background rejection power for the searches proposed, up to 10¹⁵ POT’s

The current NA62 run will be exploited to:
   - evaluate background rejection capability up to ~10¹⁷ – 10¹⁸ POT’s
   - understand how to optimize design for future beam-dump mode including, if needed, minor modifications to the existing apparatus
Spare slides
Future visible A’ search: SeaQuest @FNAL

**SeaQuest**: 120-GeV p beam from FNAL main injector

Phase 1: $\mu+\mu$- displaced pairs, $1.44 \times 10^{18}$ POT in 2017-2019

Phase 2: intensity upgrade, all final states

Phase 1 proposal (P1067) endorsed by FNAL director

**Beam**
120 GeV proton from Main Injector
19ns RF, 4s spill, $0.5 \times 10^{13}$ protons per spill

**Target system**
Liquid H and D
Solid C, Fe, W

**Focusing magnet and solid Fe dump**
$\Delta p_t = 2.9$ GeV

**Spectrometer magnet**
$\Delta p_t = 0.4$ GeV

**Absorber wall and muon ID**
(based on proportional tubes)

Ming Liu @ Dark Sectors 2016
# Present/future of MeV-GeV A’

## Vector portal: visible search

<table>
<thead>
<tr>
<th>Name</th>
<th>Where</th>
<th>Source</th>
<th>Intensity</th>
<th>Production mode</th>
<th>Detection mode</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle-II</td>
<td>Super KEK-B</td>
<td>$e^+e^- \rightarrow \Upsilon(3S)$</td>
<td>$&gt; 100 \text{ fb}^{-1}$</td>
<td>$\Upsilon(3S) \rightarrow \gamma A'$</td>
<td>$A' \rightarrow e^+e^-, \mu^+\mu^-$</td>
<td>Commis. 2018</td>
</tr>
<tr>
<td>Apex</td>
<td>JLAB</td>
<td>$e^-, 2 \text{ GeV}$</td>
<td>$10^9 \text{ EOT \ (W)}$</td>
<td>$\gamma A'$-strahlung</td>
<td>$A' \rightarrow e^+e^-$</td>
<td>Commis. 2018</td>
</tr>
<tr>
<td>HPS</td>
<td>CEBAF12 @ JLAB</td>
<td>$e^-, 1-2 \text{ GeV}$</td>
<td>$10^{14} \text{ EOT \ (W)}$</td>
<td>$\gamma A'$-strahlung</td>
<td>$A' \rightarrow e^+e^-$</td>
<td>Running 2016-20</td>
</tr>
<tr>
<td>MAGICX</td>
<td>MESA @ Mainz</td>
<td>$e^-, 155 \text{ MeV}$</td>
<td>$10^{16} \text{ EOT \ (Xe gas)}$</td>
<td>$\gamma A'$-strahlung</td>
<td>$A' \rightarrow e^+e^-$</td>
<td>Commis. 2020</td>
</tr>
<tr>
<td>Mu3e</td>
<td>πE5 line @ PSI</td>
<td>$\mu^-, 28 \text{ MeV}$</td>
<td>$10^{15-16} \mu^-$</td>
<td>$\mu \rightarrow \nu\nu A'$</td>
<td>$A' \rightarrow e^+e^-$</td>
<td>Commis. 2017</td>
</tr>
<tr>
<td>ATLAS/CMS</td>
<td>LHC @ CERN</td>
<td>$pp, 8, 13 \text{ TeV}$</td>
<td>few $\text{ fb}^{-1}$</td>
<td>$H \rightarrow 4f + \text{ MET}$</td>
<td>$A' \rightarrow \mu^+\mu^-$</td>
<td>Running</td>
</tr>
<tr>
<td>LHCb</td>
<td>LHC @ CERN</td>
<td>$pp, 13 \text{ TeV}$</td>
<td>15 $\text{ fb}^{-1}$</td>
<td>$D^+ \rightarrowDA'$</td>
<td>$A' \rightarrow e^+e^+, \mu^+\mu^-$</td>
<td>Running</td>
</tr>
<tr>
<td>NA62</td>
<td>SPS @ CERN</td>
<td>$p, 400 \text{ GeV}$</td>
<td>$2 \times 10^{18} \text{ POT}$</td>
<td>Meson, $A'$-strahlung</td>
<td>$A' \rightarrow e^+e^+, \mu^+\mu^-$</td>
<td>Running - 2018</td>
</tr>
<tr>
<td>SeaQuest</td>
<td>Main Inj. @ FNAL</td>
<td>$p, 120 \text{ TeV}$</td>
<td>1.5 $10^{18}$</td>
<td>Meson, $A'$-strahlung</td>
<td>$A' \rightarrow e^+e^+, \mu^+\mu^-$</td>
<td>Proposed 2017-19</td>
</tr>
<tr>
<td>SHiP</td>
<td>SPS @ CERN</td>
<td>$p, 400 \text{ GeV}$</td>
<td>$2 \times 10^{20} \text{ POT}$</td>
<td>Meson, $A'$-strahlung</td>
<td>$A' \rightarrow e^+e^+, \mu^+\mu^-$</td>
<td>Proposed 2026</td>
</tr>
</tbody>
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## Vector portal: invisible search

<table>
<thead>
<tr>
<th>Name</th>
<th>Where</th>
<th>Source</th>
<th>Intensity</th>
<th>Production mode</th>
<th>Detection mode</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babar</td>
<td>PEP-II @ SLAC</td>
<td>$e^+e^- \rightarrow \Upsilon(3S)$</td>
<td>57 $\text{ fb}^{-1}$</td>
<td>$\Upsilon(3S) \rightarrow \gamma A'$</td>
<td>Single-$\gamma$ trigger</td>
<td>ICHEP 2016</td>
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<tr>
<td>VEPP-3</td>
<td>VEPP-3 @ Budker Inst.</td>
<td>$e^+, 500 \text{ MeV}$</td>
<td>1.5 MHz $\gamma\gamma$</td>
<td>$e^+ e^- \rightarrow A'\gamma$</td>
<td>detect $\gamma + M_{\text{miss}}$</td>
<td>Proposed</td>
</tr>
<tr>
<td>PADME</td>
<td>BTF @ Frascati INFN</td>
<td>$e^+, 550 \text{ MeV}$</td>
<td>15 Hz $\gamma\gamma$</td>
<td>$e^+ e^- \rightarrow A'\gamma$</td>
<td>detect $\gamma + M_{\text{miss}}$</td>
<td>Approved, 2017-19</td>
</tr>
<tr>
<td>MMAPS</td>
<td>CESR @ Cornell</td>
<td>$e^+, 5.3 \text{ GeV}$</td>
<td>2.2 MHz $\gamma\gamma$</td>
<td>$e^+ e^- \rightarrow A'\gamma$</td>
<td>detect $\gamma + M_{\text{miss}}$</td>
<td>Not funded</td>
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<tr>
<td>NA64</td>
<td>SPS @ CERN</td>
<td>$e^-, 100 \text{ GeV}$</td>
<td>$e^- N \rightarrow e^- NA'$</td>
<td>$10^{29-10} \text{ EOT}$</td>
<td>detect $e^- + E_{\text{miss}}$</td>
<td>Running, 2016-17</td>
</tr>
<tr>
<td>LDMX</td>
<td>LCLS-II @ SLAC</td>
<td>$e^-, 4 \text{ GeV}$</td>
<td>$e^- N \rightarrow e^- NA'$</td>
<td>$10^{15-10} \text{ EOT}$</td>
<td>detect $e^- + E_{\text{miss}}$</td>
<td>Proposed, 2020</td>
</tr>
</tbody>
</table>

## Vector portal: DM search

<table>
<thead>
<tr>
<th>Name</th>
<th>Where</th>
<th>Source</th>
<th>Intensity</th>
<th>Production mode</th>
<th>Detection mode</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBND</td>
<td>FNAL</td>
<td>$p, 9 \text{ GeV}$</td>
<td>$2 \times 10^{20} \text{ POT}$</td>
<td>Meson, $A'$-strahlung $A' \rightarrow \varphi\varphi$</td>
<td>detect $\phi @ 110 \text{ m}$</td>
<td>Under study</td>
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<tr>
<td>T2K</td>
<td>Tokai-Kamioka</td>
<td>$p, 30 \text{ GeV}$</td>
<td>$10^{21} \text{ POT}$</td>
<td>Meson, $A'$-strahlung $A' \rightarrow \varphi\varphi$</td>
<td>detect $\phi @ 280 \text{ m}$</td>
<td>Running</td>
</tr>
<tr>
<td>COHERENT</td>
<td>SNS @ Oak Ridge</td>
<td>$p, 1 \text{ GeV}$</td>
<td>$10^{23} \text{ POT}$</td>
<td>Meson, $A'$-strahlung $A' \rightarrow \varphi\varphi$</td>
<td>detect $\phi @ 20 \text{ m} \text{ 2}\text{r}.\text{OA}$</td>
<td>Proposed</td>
</tr>
<tr>
<td>SHiP</td>
<td>SPS @ CERN</td>
<td>$p, 400 \text{ GeV}$</td>
<td>$2 \times 10^{26} \text{ POT}$</td>
<td>Meson, $A'$-strahlung $A' \rightarrow \varphi\varphi$</td>
<td>detect $\phi @ 100 \text{ m}$</td>
<td>Proposed 2026</td>
</tr>
<tr>
<td>LBNF</td>
<td>DUNE @ FNAL</td>
<td>$p, 120 \text{ GeV}$</td>
<td>$3 \times 10^{27} \text{ POT}$</td>
<td>Meson, $A'$-strahlung $A' \rightarrow \varphi\varphi$</td>
<td>detect $\phi @ 500 \text{ m}$</td>
<td>Under study 2020</td>
</tr>
</tbody>
</table>

Some of the above will address neutrino portal, too: neutrino experiments, NA62, SHiP

Some of the above will address ALP portal, too: NA62, SHiP
1. **Kinematics**, rejection of main K modes $10^4$—$10^5$ via kinematic reconstruction:

- 75 GeV K decay to low-momentum $15 < p < 35$ GeV daughter pion, **both** tracked
- Si-based stations upstream (GTK): $\sigma(p_K)/p_K \sim 0.2\%$, $\sigma(\theta_K, \phi_K) \sim 16$ $\mu$rad
- Straw-tubes in-vacuum downstream: $\sigma(p_\pi)/p_\pi < 1\%$, $\sigma(\theta_\pi, \phi_\pi) \sim 60$ $\mu$rad
How to identify open-signature $K \rightarrow \pi \nu \nu$

2. PID capability, $\mu$ vs $\pi$ rejection of $O(10^7)$:
   better rejection in the low-momentum range, $15 < p < 35$ GeV
   $10^2$ from RICH with efficiency of 80%
   $10^4$—$10^6$ from calorimeters with efficiency 90%—40%
How to identify open-signature $K \rightarrow \pi \nu \nu$

3. Hermetic, high-energy veto of additional photons:
   - $10^8$ rejection of $\pi^0$'s: $p < 35 \text{ GeV} \rightarrow E(\pi^0) > 40 \text{ GeV}$
   - Three systems covering angle range $\theta < 50 \text{ mrad}$: LAV, LKr, IRC/SAC

![Diagram of particle physics experiment with labels and angles]